

## Life cycle assessment of energy generation from biogas—Attributional vs. consequential approach

T. Rehl<sup>\*</sup>, J. Lansche<sup>1</sup>, J. Müller<sup>2</sup>

University of Hohenheim (440e), Institute of Agricultural Engineering, Garbenstraße 9, 70599 Stuttgart, Germany

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### ABSTRACT

Many studies that apply life cycle assessment methodology avoid a strict differentiation between attributional (aLCA) and consequential (cLCA) life cycle assessment. The main distinction that can be made is that an aLCA approach describes a state of average production systems of an economic system while in contrast the consequential approach describes changes (induced by political decisions) in production systems within the economic system. The task of this study was to analyze a biogas system from an environmental point of view and thereby to work out the methodological differences of aLCA and cLCA approaches. The Life cycle inventory quantity primary energy demand (PED) as well as the impact categories global warming potential (GWP), eutrophication (EP), acidification (AP) and photochemical ozone creation potential (POCP) were analyzed. The aLCA approach was split into three scenarios, a physical, an economic and a core product focused one (with focus on the main product) to show the impact of by-product handling. The cLCA approach was split into a local scenario using on-site data and a general scenario using higher aggregated data to show the effects of substitution caused by the introduction of a new technology. The results of the two approaches were compared with the environmental impact of the current average and marginal German electricity mix. Global warming potential per functional unit varied between 3.8 g and 12.5 g of CO<sub>2</sub> equivalent in the biogas scenarios. Compared to the average and marginal German electricity mix savings in PED, GWP and partly in AP and POCP can be achieved. However, high variations in the proportion to the reference electricity system, the total quantity results as well as the contribution of single processes to the total result were found. This makes it indispensable to distinguish accurately between the aLCA and the cLCA approach.

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\* Corresponding author. Present/permanent address: PE-INTERNATIONAL, Hauptstraße 113-115, 70771 Leinfelden-Echterdingen, Germany.  
Tel.: +49 0711 34 18 17 72; fax: +49 0711 34 18 17 24.

E-mail addresses: [t.rehl@pe-international.com](mailto:t.rehl@pe-international.com), [torsten.rehl@uni-hohenheim.de](mailto:torsten.rehl@uni-hohenheim.de) (T. Rehl), [j.lansche@uni-hohenheim.de](mailto:j.lansche@uni-hohenheim.de) (J. Lansche), [joachim.mueller@uni-hohenheim.de](mailto:joachim.mueller@uni-hohenheim.de) (J. Müller).

<sup>1</sup> Tel.: +49 0711 459 23112; fax: +49 0711 459 23298.

<sup>2</sup> Tel.: +49 0711 459 22490; fax: +49 0711 459 23298.

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## 1. Introduction

Frequently, there are two goals for performing a life cycle assessment (LCA) study: (i) to analyze the environmental impacts throughout a product's life (i.e. from cradle to grave), (ii) to advise policy-making through a comparison of environmental impact of various alternative products or systems. In LCI modeling two main principles are frequently applied in parallel to achieve these goals: the attributional LCA (aLCA) and the consequential LCA (cLCA).

The attributional life cycle assessment (aLCA) has been introduced by Heijungs [1]. It is also referred to as "accounting", "average", "book-keeping", "descriptive", "non-marginal" or "retrospective" method. The focus of the aLCA approach lies on the analysis of environmental impacts of a product, a process or a system. It was developed to address preventive environmental protection in decision making processes to reduce potential risks to the environment. In aLCA allocations are based on average data and the relative value of the products and co-products [2]. In LCA modeling allocation is the most characteristic difference between aLCA and cLCA approach. The aLCA approach uses physical properties such as mass, heating or economic value ratios of products to isolate the percentage share of resource demand and the emissions of pollutants from individual product flows [3]. The idea is to determine the impact of the functional unit (FU) chosen to characterize a production system. According to UNFCCC [4] different definitions based on the economic revenue for co-products, by-products and residues/wastes should be used to systematize the allocation procedure:

- **Co-products:** Products that are produced along with the main product having similar financial revenues as the main product.
- **By-products:** Products that are produced along with the main product having smaller financial revenues than the main product.
- **Residue/waste products:** Products that are generated along with the main product but have no or negligible revenues.

The consequential life cycle assessment (cLCA) is also called "change-oriented", "market-based", "marginal" or "prospective" method. The approach is used to identify the technology affected by a change in demand. The term "consequential model" has been extensively discussed during an LCA workshop held in Cincinnati, OH, USA and was described and applied in the following years by various authors [5–10]. The marginal technology is defined as the technology or the technology mix, which is substituted by a new technology under consideration of market aspects and technology specific availability. In contrast to the attributional approach, where average (not marginal) technologies are used, the cLCA approach is applied to obtain information about the changes in pollution and resource flows caused by a change in demand or in the output of the functional unit [6,8]. In the cLCA approach "system expansion" and "substitution", also called "system enlargement" or "crediting" is used to solve multi-functionality (processes with more than one output product) of a process. The cLCA approach ensures the equality of multi-functional product systems by substituting the products, which are not in the focus of the analysis with alternative ways of providing it [2]. The aim of a biogas-cLCA is to assess the total environmental impact caused by the introduction of a new biogas system and the replacement or the avoidance of a reference

system or "business as usual" system. The overall goal is to inform decision-makers about the consequences of decisions concerning an additional amount of electricity from biogas production on the market. It is a matter of finding out if the individual decision about the production of a supposed environmentally friendly product has really led to a reduction in environmental impacts. This led to the following main question for this study: "What are the environmental implications of supplying the market with energy from biogas technology?" The analysis includes both, the direct effects of replacing various energy carriers and energy systems, and indirect effects of changed handling of feedstock, e.g. digestate management and farming practice.

So far, in many LCA studies about energy generation from biogas no differentiation between aLCA and cLCA was carried out and frequently the main instruments of aLCA and cLCA modeling, viz. allocation and system expansion, were mixed arbitrarily. The objective of this study was to apply both approaches separately to the same case "electricity generation from biogas", to investigate, whether there are significant differences in the results. Further objective was to identify and discuss the advantages and disadvantages of attributional and consequential modeling.

## 2. Methodology

### 2.1. General assumptions

The analysis was done based on the guidelines for LCA according to DIN EN ISO 14040:2006/14044:2006 [11]. To make the biogas systems comparable for aLCA and cLCA, the basis of comparison, i.e. the output in form of fertilizer or energy services, must be the same in both systems. Therefore, the functional unit was chosen to be 1 MJ of electricity supplied to the electricity network. The system boundary of this LCA is cradle-to-gate. Primary energy demand is used as an indicator for resource depletion. It includes the overall energy consumed in the production process and the energy stored in the products. Renewable energy from sun light stored in the feedstock of the biogas plant was not considered within this study. The CML method [12] developed by the Centrum voor Milieukunde in Leiden, Netherlands (CML) was chosen to assess inventory flows for the impact categories: global warming potential, acidification potential, eutrophication potential and photochemical ozone creation potential. Background data for the biogas system as well as the reference system were taken from the GaBi database [13], which was extended by data from the ELCD database [14] and the ECO-Invent integrated database [15]. Biogas system modeling, data administration, classification, characterization, analyzing and weighting were done with GaBi 4.3 software. Emissions and resource consumption by the production of buildings and machinery are not included as most aspects of agricultural infrastructure do not have a significant impact on the total LCA [16].

### 2.2. System description

In Table 1 the main features of the biogas plant and the emission rates from on-site measurements [17] are shown. Specific data (e.g. electricity, and heat demand of biogas plant) from a research plant of the University of Hohenheim was used. The data were amended by literature data and used to set up a fictive but representative

**Table 1**

Power, feedstock and emission characteristics of the biogas combined heat and power plant (CHP).

Parameter	Unit	Value
Electrical power installed	kW <sub>el</sub>	186
Engine type: gas engine		
Electrical efficiency	$\eta_{el}$	0.39
Thermal efficiency	$\eta_{th}$	0.46
Feedstock (total)	t/a	6040
Liquid manure	t/a	3860
Solid manure	t/a	860
Maize ensilage	t/a	760
Grass ensilage	t/a	240
Grain	t/a	320
Emission rates		
CH <sub>4</sub>	g/h	563
SO <sub>2</sub>	g/h	1.17
NO <sub>x</sub>	g/h	281
CO	g/h	452

biogas system for German conditions. The biogas plant is main part of a research project financed by the Federal Ministry of Agriculture in Baden Württemberg. The biogas plant is located 48.5°N, 9.3°E, 480 m above sea level with a mean temperature of 11 °C and an annual precipitation of 894 mm. The farm is cultivating 40 ha of arable land and 123 ha of enclosed pasture. Animal husbandry comprises cattle, pigs, goats and poultry. Energy crops are fermented together with liquid and solid manure from animal husbandry using two-stage digestion technology operated in a continuous flow at mesophilic temperatures. Two vertical digesters each with a volume of 923 m<sup>3</sup> are combined with a gas-proof post-fermenter, built with monolithic concrete. Different heater loops and stirring devices are installed to be compared with regard to electricity input. Biogas produced in the fermentation process is cooled down in a buried pipe to reduce the water content of the biogas by condensation. Afterwards the biogas is combusted in a 186 kWel gas engine used as CHP. The engine is designed to produce 1.46 MWh of electricity and 1.59 MWh of heat per year. The electrical energy generated is supplied to the electricity network. Surplus heat of the research biogas plant, which is not used for heating the fermenter, is fed into the distribution network of the farm for heat supply of farm facilities and private houses. Annual, 18% of the heat is used for heating the fermenter.

The biogas model was set up as a generic model, which allows to reproduce material and energy flows and to model supply chains from different sources (e.g. manure, energy crops) separately. For each of the feedstock pathways a biogas system was set up in GaBi software and each of it uses mass scaled generic model processes (cultivation, ensilage, conveyor technologies, fermentation, storage, etc.). Fermentation process is the main generic process, which was computed based on fugitive emission factors developed by Baserga [18] and biogas yield experiments performed by Amon [19]. To be able to allocate resource use and environmental impacts to single contributors, self energy demand of single processes e.g. pumps, stirring devices, conveyor belts, etc. was calculated based on the electrical power, throughput and running time of each device. Heat self energy demand was calculated based on the amount of energy necessary for heating up the feedstock to the fermentation temperature of 38 °C and the heat loss through the fermentation tank using the specific heat transition coefficient of the materials. Furthermore, the biogas plant model considers biogas dewatering by buried pipe and biological biogas purification (desulfurization by bacteria within the fermenter). Life Cycle Inventory of corn, grass and grain supply chains includes cultivation, harvest, shredding, transport and ensilage. Energy crop production includes fertilizing, machinery working processes,

pesticide application, decomposition of nitrogen and carbon in the soil; transport contains tractor work from field to farm, on-farm transport processes by wheel loader, tractor and conveyor belt or auger as fermenter feeder. Ensilage processing was considered by taking leakage water, as well as 7.5% of organic degradation into CO and CO<sub>2</sub> into account. On the output side digestate is leaving the fermentation process with average dry matter content of 7.3%. Digestate is stored in open tanks with natural crust cover. Spreading liquid phase of digestate is carried out by a tractor with broadcast spreader while spreading the solid phase is assumed to be carried out by a compost spreader. After application of digestate to arable land it is mostly incorporated within 4 h. The correlation of duration between application and incorporation of manure and the amount of ammonia (NH<sub>3</sub>) volatized to air is considered. All nitrogen based emissions of ammonia (NH<sub>3</sub>); nitrate (NO<sub>3</sub><sup>−</sup>), nitrous oxide (N<sub>2</sub>O), nitrogen oxide (NO) and nitrogen (N<sub>2</sub>) from storage and application were calculated based on data for cattle, according to the national emissions inventory of Germany [20]. Emissions from storage were calculated for an open storage tank with natural crust cover for the digestate. The emission factor for NH<sub>3</sub> is 0.1169 and 0.005 for N<sub>2</sub>O emissions, while NO and N<sub>2</sub> emissions are calculated based on a fixed ratio recommended by Jarvis [21]. According to Jarvis NO emission are three times higher and N<sub>2</sub> ten times higher than those of N<sub>2</sub>O. Field application of digestate is done by broadcast technology. Methane emissions during storage were calculated according to IPCC [22] using a methane emission factor (MCF) of 0.1 kg per kg carbon in the digestate and a methane creation potential ( $B_0$ ) of 0.172 kg CH<sub>4</sub> per kg organic dry matter. Uncontrolled methane emissions of the biogas plant from leakages were estimated to be 2% of total methane production based on the literature data [23–26].

### 2.3. Allocation procedure

The GaBi and ELCD background datasets were used for setting up of the biogas model using different allocation methods depending on the specific process, such as allocation according to exergy for a combined heat and electricity generation plant. The effect of those allocations was not considered within the scope of the present study. Allocation procedure was performed at the following three locations of multi output production: At first at livestock production between milk, meat and manure, secondly at biogas production between biogas and digestate, and thirdly for energy production between electricity and heat at the CHP.

After fermentation the main product biogas is converted in the CHP and the digestate is stored in tanks and applied as organic fertilizer to food, feed or energy crops. The digestate contributes on the one hand positively to the environment as plant nutrients like N, P, K are contained, which substitute mineral fertilizer but on the other hand affects the environment negatively as nitrogen emissions are released in different forms during storage and field application. Digestate can be distinguished into digestate originating from feedstock specifically provided for biogas production (e.g. energy crops) and digestate coming from sources like manure from livestock husbandry. Digestate coming from fermentation of corn ensilage was recycled back to fields for corn cultivation. If biogas digestate originates from another system (e.g. animal husbandry with on- and ex-farm produced fodder) it is necessary to allocate the emissions between the biogas and the animal husbandry system. The way of solving multi functionality is presented in the following two sections.

### 2.4. Attributional approach

Fig. 1 shows the aLCA flowchart of the biogas plant system based on average diesel and electricity data on the input side and locations

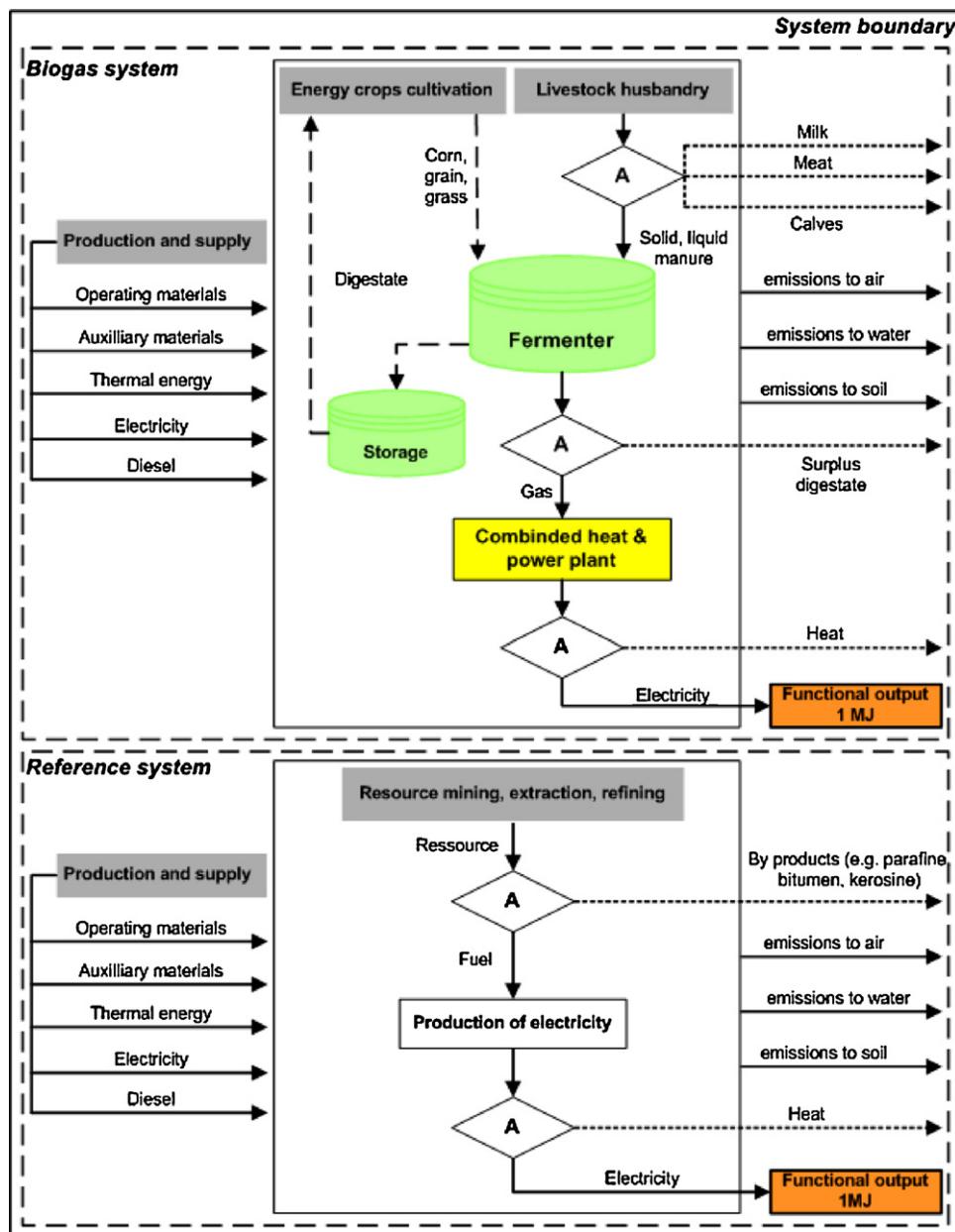


Fig. 1. System boundary, energy, material and emission flows for attributional life cycle assessment (aLCA) of a biogas system.

of allocation procedures for multi product processes on the output side of the biogas system.

Physical, economic and core product focused allocation scenarios were developed in the aLCA approach: aLCA<sub>physical</sub>, aLCA<sub>economic</sub> and aLCA<sub>core product</sub>. Table 2 presents the resulting allocation factors for each scenario. The allocation factors are presented for each of the five feedstock inputs.

In the physical allocation scenario the mass ratio was chosen for allocation procedure between manure, milk and meat (including old dairy cows and calves to be slaughtered) and between biogas and digestate. Mass allocation distributes 83% of the burden from livestock husbandry to liquid manure and 91% of the burden from biogas production to digestate and only 9% to the biogas product. Energy allocation would use the lower calorific value of the fresh products (milk, meat, manure, etc.). However, the lower calorific value of milk, manure and digestate is zero and thereby not applicable for allocation procedure at this stage. Physical

allocation scenario uses the amount of electricity and heat for allocation at the CHP; thereby 57% of the environmental burdens were allocated to the by-product heat. It is obvious that this way of allocation does not consider the quality of the energy and the motivation for processing. Therefore an economic scenario was developed. Usually the products biogas, manure and digestate are not sold by the farmer. Consequently, farm gate prices do not exist. Therefore, virtual prices were developed based on cross calculated prices for biogas based on prices for natural gas (0.441 €/kg) according to the European Energy Exchange [27] and digestate (0.008 €/kg) according to the economic value of N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O [28]. In the “core” approach allocation between milk, meat & manure and between biogas and digestate motivation on the main product was chosen. In this case by-products such as solid and liquid manure were provided without environmental burdens to the biogas system. At the CHP exergy factors were applied in the allocation procedure. Exergy is a measure of the quality of an

**Table 2**

Allocation factors (in %) for main and by-products in a biogas system for physical, economic and core product allocation in the aLCA approach for different feedstock sources.

		Physical (%%)	Economic (%%)	Core product (%%)
Solid manure	Sm-Lm–livestock products	80.8–2.1–17.1	3.0–1.3–95.6	0–0–100
	Biogas–digestate	12.1–87.9	76.2–23.8	100–0
	Electricity–heat	44.8–55.2	78.8–21.2	93.9–6.1
Liquid manure	Sm-Lm–livestock products	80.8–2.1–17.1	3.0–1.3–95.6	0–0–100
	Biogas–digestate	0.7–99.3	50.2–49.8	100–0
	Electricity–heat	45.1–54.9	100–0	100–0
Grass	Electricity–heat	49.0–51.0	84.9–15.1	90.6–9.4
Corn	Electricity–heat	49.8–50.2	83.2–16.8	90.8–9.2
Wheat	Electricity–heat	43.6–56.4	81.0–19.0	88.5–11.5

Sm: solid manure; Lm: liquid manure.

energy form. Exergy factors of 1 for electricity and 0.1 for heat for a temperature of 50 °C were applied in the aLCA scenario resulting in an allocation ratio of 91% for electricity and 9% for heat.

## 2.5. Consequential approach

Fig. 2 shows a flow chart of the cLCA approach. In the cLCA approach multi functionality of the biogas system was dissolved by the “system expansion approach”, as recommended by ISO 14044 [11]. The system expansion approach is based on expanding the system to include alternative product systems for the functions: manure, digestate, area use and heat. The cLCA approach can be summarized as follows: The environmental profile of a biogas cLCA system is the difference of a farm with a biogas plant compared to a farm without biogas plant plus the difference of avoided or produced emissions correlated to the substituted marginal technology to produce heat. The cLCA approach was divided into two scenarios to bring out the effects of marginal technology substitution on different levels of aggregation: (i) a local scenario with data of the real situation at the farm (cLCA<sub>local</sub>) and (ii) a general scenario with average data at a higher (national) level of aggregation for general validity (cLCA<sub>general</sub>).

The implementation of a biogas plant into an existing farming system usually does not have an impact on the technical organization of the livestock husbandry system. However, the manure management system of the farm is influenced by a demand of additional storage capacity for the additional amount of digestate generated from energy crop fermentation. This makes it necessary to replace the old manure storage by a new storage tank with a natural crust cover, in both the biogas and the marginal system (assumed in cLCA<sub>local</sub> scenario). To identify the marginal system in the cLCA<sub>general</sub> scenario a significant trend was identified from national statistics. According to DESTATIS [29,30] the storage of manure underneath the slatted floor is strongly decreasing during the last 20 years in Germany (from 39% in 1999 to 29% in 2010). Therefore, this technology was assumed to be replaced by a new system. The storage of manure underneath the slatted floor is characterized by a NH<sub>3</sub> emission factor of 0.163 kg per kg excreted nitrogen. As recommended by Dämmgen [20] nitrogen based emissions factors of N<sub>2</sub>O, N<sub>2</sub>, NO and carbon based emission factor of CH<sub>4</sub> of liquid manure management stays the same compared to the biogas system. Solid manure in the marginal system is stored in open heaps with an NH<sub>3</sub> emission factor of 0.60 kg per kg N. Methane emissions of solid manure lean on the methodology used for the calculation of methane emissions from digestate management. Again a methane emission factor of 0.1 kg per kg carbon in the solid manure was applied along with a methane creation potential ( $B_0$ ) of 0.24 kg CH<sub>4</sub> per kg organic dry matter. The manure field application technology is not affected by the biogas technology since the broadcast is applicable for both the untreated manure as well as the digestate. Emissions of NH<sub>3</sub>, NO, N<sub>2</sub>O, N<sub>2</sub> from different storage technologies resulting in differences in the nutrient

balance of the new and the avoided system, were calculated. The amount of surplus or deficit nutrients was assumed to be compensated by mineral fertilizer. Data on the marginal mineral fertilizer production was taken from Destatis [29], where the most important sources of primary nutrients for German agriculture are listed. The fertilizers are: calcium ammonium nitrate as source of nitrogen, super phosphate as a source for P<sub>2</sub>O<sub>5</sub> and potassium chloride as a source for K<sub>2</sub>O. Emission data concerning mineral fertilizers production are taken from the Ecoinvent 2.0 database [15].

The area covered by energy crops replaces a specific marginal area use which is considered within the present study for both, the local and the general scenario. In Germany the amount of fallow land is recurrently adopted according to European Commission regulatory depending on the local market situation of food. From 2008 to 2010 the area was fixed at a rate between 5 and 10% of total arable land. This area was assumed to be available for the cultivation of the energy crops. Emissions going along with fallow land were considered using emission factors for N<sub>2</sub>O according to IPCC [22], NH<sub>3</sub>, NO according to Dämmgen, NO<sub>3</sub><sup>–</sup> according to Brentrup [31,32] and the crop model of PE INTERNATIONAL, Leinfelden-Echterdingen (Germany) [13].

Direct marginal inputs to the biogas system are diesel, electricity and fermentation feedstock. Diesel supply chains vary depending on source and region. Since additional use of diesel induced by the biogas process will have minor impact, the effect of different diesel supply chains was neglected and the average diesel mix for Germany was used. The increased electricity demand was considered using data representing technologies that are expected to be substituted with this increase. The German electricity network is spread and interlinked across the entire national area resulting in a specific marginal German electricity mix (GEMm). The substitution factors for the marginal electricity mix of Germany in 2007 were taken from Klobasa [33]. The marginal electricity mix was also taken as the reference system for the marginal system to identify the impacts induced by the biogas system. Finally, a marginal technology for the by-product heat was defined. For the technology avoided by a change in demand an approach used by Memmler et al. [34] was applied, assuming that heat produced by agricultural biogas plants usually is used in the near surrounding of the biogas plant, e.g. for farmsteads and stables. Hence, it was assumed that the heat substituting a marginal heat mix of fossil fuels used by farms and companies in rural areas in Germany. The substituted heat was accounted according DESTATIS data [29], which was 46% natural gas, 48% fuel oil and 6% coal (Table 3).

## 3. Results and discussion

### 3.1. Primary energy demand

As presented in Fig. 3, the overall primary energy demand of the aLCA and the cLCA scenarios are lower than their corresponding reference system. The average electricity mix consumes 2.9 MJ and

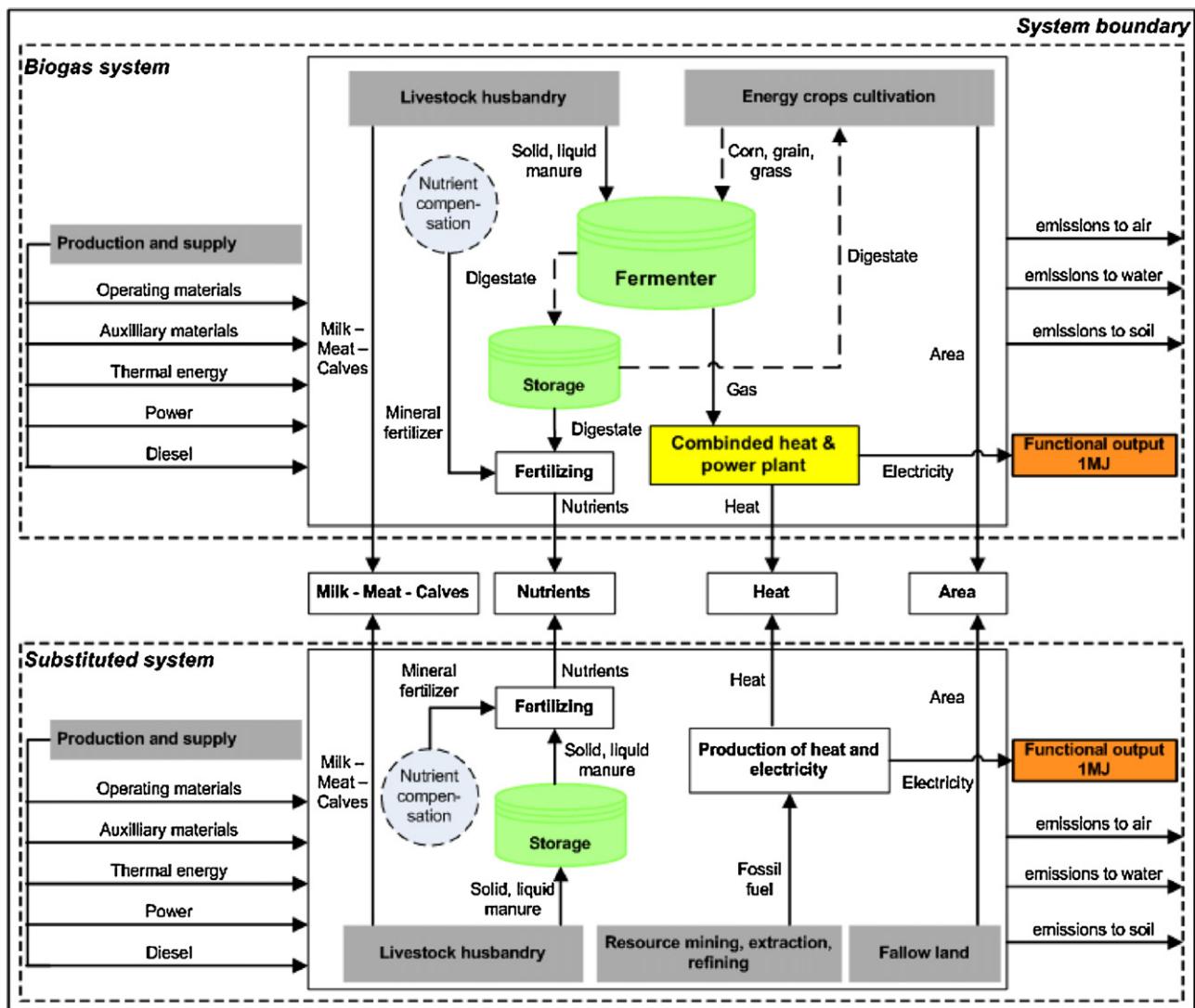


Fig. 2. System boundary, energy, material and emission flows for consequential life cycle assessment (cLCA) of a biogas system.

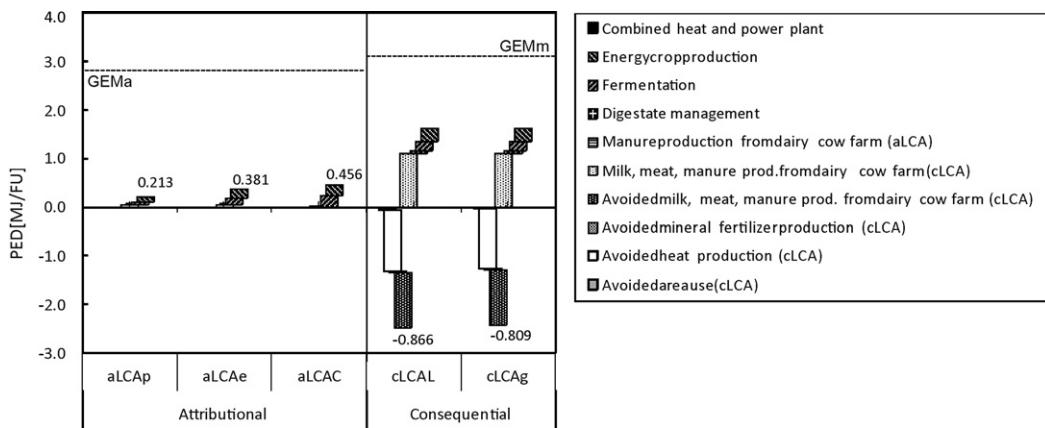
the marginal electricity mix 3.1 MJ of energy to generate 1 MJ of electricity. However, while aLCA scenarios consume energy, cLCA scenarios generate a net credit of energy. This implies that each MJ of electricity generated by a biogas plant under the given assumptions and the current energy market would save 0.8–0.9 MJ of primary energy. The positive effects are created mainly by credits of avoided production of heat and to a much lower extend by

avoided reference land use and avoided production and field application of mineral fertilizer. Credits of mineral fertilizer are obtained from (i) lower losses of nitrogen from digested solid manure compared to solid manure storage and field application and (ii) by lower nitrogen losses of the storage system compared to the avoided one. Observing aLCA scenarios, aLCA<sub>physical</sub> shows the lowest demand of primary energy—which is less than half of the primary energy in

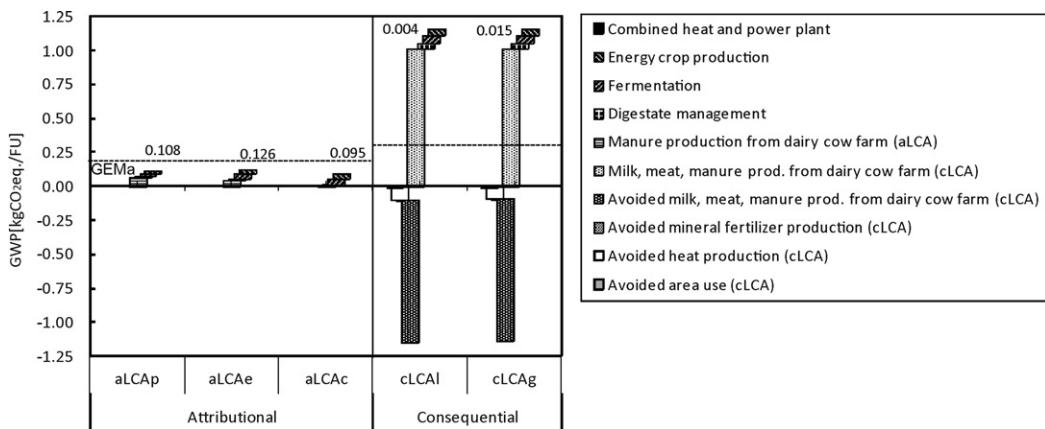
Table 3

Marginal technologies used in scenario cLCA<sub>local</sub> and cLCA<sub>general</sub> to provide the system functions of the biogas system under consideration.

	Local	General
Milk, meat	Milk, meat provided by specific local farm	Milk, meat provided by general national farm
Area	Fallow land	Fallow land
Nutrient provision	Nutrients N, P, K provided by liquid manure (stored in open tanks with natural crust and applied with manure spreader) Nutrients N, P, K provided by solid manure stored in open heaps Nutrient (N, P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O) compensation by mineral fertilizer	Nutrients N, P, K provided by liquid (stored in the cowshed underneath the slatted floor and applied with manure spreader) Nutrients N, P, K provided by solid manure stored in open heaps Nutrient (N, P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O) compensation by mineral fertilizer German heat mix (46% natural gas, 48% fuel oil and 6% coal)
Heat	Oil heating boiler	
Electricity	German marginal electricity mix (1% lignite, 66% hard coal, 32% natural gas and 1% mineral oil)	



**Fig. 3.** Primary energy demand (PED) per functional unit (FU, 1 MJ supplied electricity) of three attributional life cycle assessment scenarios (aLCAp physical allocation, aLCAe economic allocation, aLCAC core product allocation) and two consequential life cycle assessment scenarios (cLCAL local, cLCAG general) of an exemplary biogas system in Germany. In A average German electricity mix (GEMa) and the marginal German electricity mix (GEMm) are indicated by dotted lines.

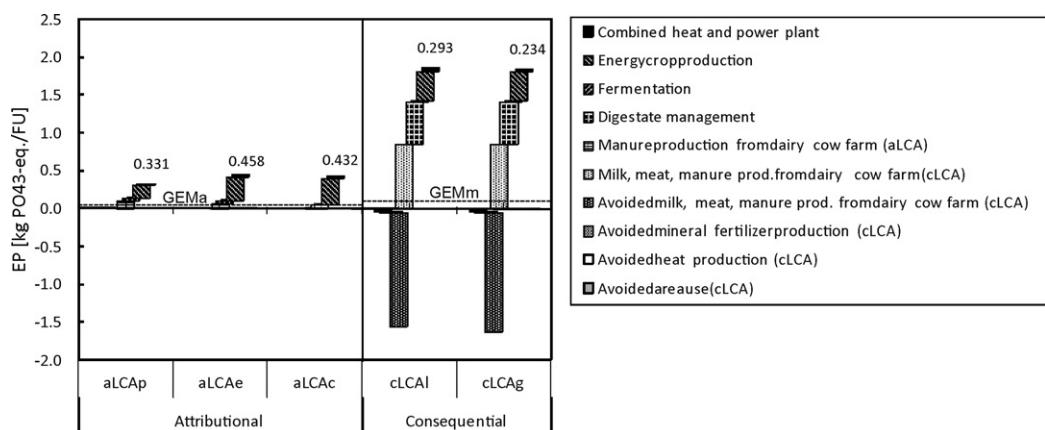


**Fig. 4.** Global warming potential (GWP) per functional unit (FU, 1 MJ supplied electricity) of three attributional life cycle assessment scenarios (aLCAp physical allocation, aLCAe economic allocation, aLCAC core product allocation) and two consequential life cycle assessment scenarios (cLCAL local, cLCAG general) of an exemplary biogas system in Germany. Average German electricity mix (GEMa) and the marginal German electricity mix (GEMm) are indicated by dotted lines.

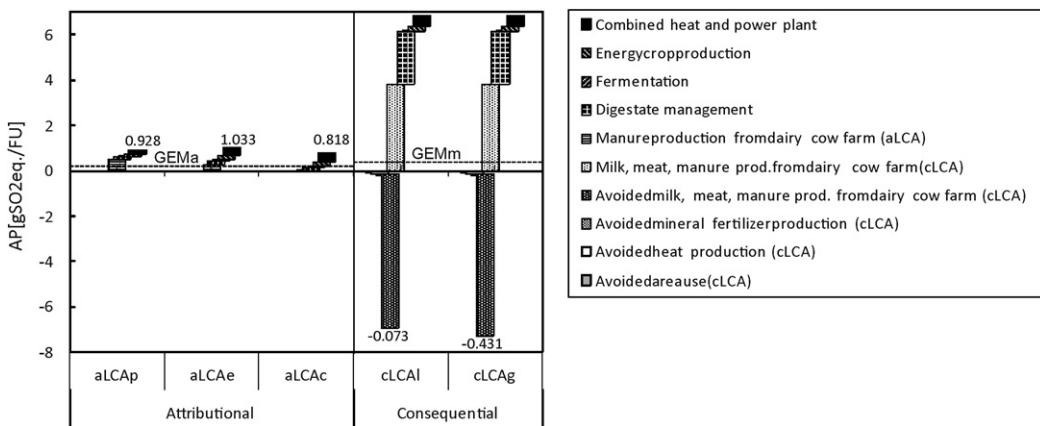
the economic and the core product motivated scenario. The strong difference within the aLCA results was induced by the allocation procedure between electricity and heat (Figs. 4 and 5).

In Fig. 3 besides the total contribution also the relative contribution of single processes is shown. Depending on the methodology used and the scenario defined different fractions of single

contributors are found. For instance the contributor “milk, meat and manure production” of the new system and the contributor “substituted milk, meat and manure production” of the avoided system represent the total impact going along with the provision of manure, milk and meat needed to produce 1 MJ of electricity. Together with the contributor digestate management the sum



**Fig. 5.** Eutrophication (EP) per functional unit (FU, 1 MJ supplied electricity) of three attributional life cycle assessment scenarios (aLCAp physical allocation, aLCAe economic allocation, aLCAC core product allocation) and two consequential life cycle assessment scenarios (cLCAL local, cLCAG general) of an exemplary biogas system in Germany. Average German electricity mix (GEMa) and the marginal German electricity mix (GEMm) are indicated by dotted lines.



**Fig. 6.** Acidification potential (AP) per functional unit (FU, 1 MJ supplied electricity) of three attributional life cycle assessment scenarios (aLCAp physical allocation, aLCAs economic allocation, aLCAc core allocation) and two consequential (cLCA) life cycle assessment scenarios (cLCAI local, cLCAG general) of an exemplary biogas system in Germany. Average German electricity mix (GEMA) and the marginal German electricity mix (GEMm) are indicated by dotted lines.

results in the impacts and the PED which have to be allocated to the new biogas system. For the PED the sum is insignificant lower compared to the marginal production of these products for both marginal scenarios (3% in cLCA<sub>local</sub> and 6% in cLCA<sub>general</sub>). In contrast to the cLCA approach in the aLCA approach manure production can easily be identified as it is directly allocated to the biogas system. The contribution to the total result is 20% in aLCA<sub>physical</sub> with physical allocation, 8% in aLCA<sub>core</sub> with economic allocation and 0.8% in aLCA<sub>core</sub> with core product motivation. However, also in the aLCA scenarios different allocation procedures result in different orders of magnitude of single contributors, e.g. between the main contributor “energy crop production” and “fermentation, biogas cleaning”.

### 3.2. Impact assessment

#### 3.2.1. Global warming potential

As already found out in several studies, fermentation is a viable option to reduce GWP—all scenarios have a significantly lower GWP compared to the average and marginal German electricity mix. However, as presented in Fig. 6 methodological assumptions have a high influence on the GHG balance and thereby on the saving potentials of the fermentation technology compared to other technologies. The possible savings vary between 52% in aLCA<sub>economic</sub> and 37% in cLCA<sub>local</sub> scenarios compared to the corresponding reference system. The high GWP reduction in cLCA scenarios compared to the German electricity mix mainly arise from credits of heat. By this means the trend which was already found in the PED observation was corroborated. The main contributor to the GWP is the energy crop production in aLCA<sub>economic</sub> and aLCA<sub>core</sub> while it is the manure production in the aLCA<sub>economic</sub> approach and in the cLCA approaches. The other hotspots within both approaches were fermentation and cleaning of biogas mainly due to diffuse methane emissions and digestate management due to N<sub>2</sub>O and CH<sub>4</sub> emissions. Within cLCA, the emissions arising from the upgraded new biogas system were around 3% lower than the avoided production of milk, manure and nutrients.

#### 3.2.2. Eutrophication potential

Reductions in the global warming potential of biogas technologies compared to the fossil fuel based electricity mix lead on the other hand to increased handling of nutrient and thereby to emissions of nitrogen compounds to air and water and phosphate to surface water. The environmental impact on eutrophication (presented in Fig. 6) of the biogas systems is, compared to the average

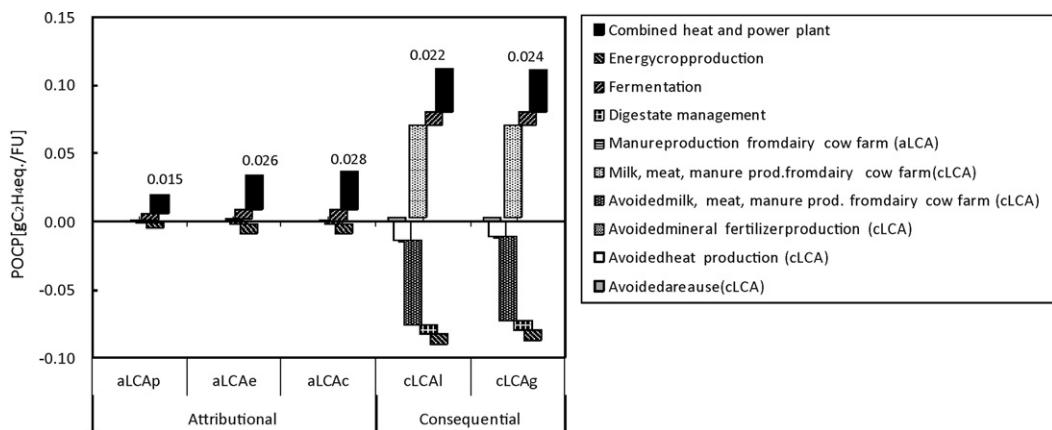
and marginal electricity mix 6 (cLCA<sub>general</sub>) up to 17 (aLCA<sub>economic</sub>) times higher. Due to the fact that heat provision by fossil fuels usually is not a significant source of EP, the difference between aLCA and cLCA scenarios in EP is lower than the differences found in GWP and PED results. However, in both LCA approaches the main source of EP relevant emissions is the digestate application to energy crops, which is responsible for nitrogen (in the form of NO<sub>3</sub><sup>–</sup>) and phosphate (in the form of PO<sub>4</sub><sup>3–</sup>) leaching to surface water.

#### 3.2.3. Acidification potential

The AP of the observed scenarios was higher than the average and lower than the marginal electricity mixes. As for the EP in the aLCA the economic and in the cLCA the local scenario shows highest AP. However, in cLCA scenarios the introduction of the biogas technology avoided more emissions than have been emitted by the new system (–0.073 in cLCA<sub>local</sub> and –0.431 in cLCA<sub>general</sub>). Credits have a significant effect on the result. They arise from avoided production of heat from fossil fuel combustion and avoided NH<sub>3</sub> emissions from storage of digestate compared to untreated storage of manure. After offsetting emissions from manure and digestate management emissions from the CHP contributed most to the acidification potential both within cLCA and aLCA. The most important contributor is sulfur dioxide from the CHP next to ammonia emissions from digestate management in energy crop production and animal husbandry.

#### 3.2.4. Photochemical ozone creation potential

The POCP of biogas systems is mainly influenced by emissions of nitrous oxide from combustion processes and the waste air cleaning technology used at the CHP. A typical NO<sub>x</sub> rate of 196 mg/m<sup>3</sup> of waste air at the flue was assumed in this study resulting in considerably lower POCP in the aLCA<sub>physical</sub> scenarios compared to the German electricity mix. Although the aLCA<sub>economic</sub>, aLCA<sub>core</sub> and the cLCA scenarios are in a same range, considerably different conclusions must be drawn, due to significant differences in the corresponding reference system (GEMm is 40% higher than GEMA). While economic and core product aLCA scenarios lead to a negative, cLCA scenarios lead to a positive assessment for decision maker regarding the implementation of the biogas technology. However, in all systems the CHP was identified to be the major contributor to potential POCP from the biogas system. Mainly sulfur dioxide emissions play a major role (92%) in the POCP category followed by nitrogen oxides (6%) and other emissions including unburned CH<sub>4</sub> and nitrogen monoxide (in sum 2%) (Fig. 7).



**Fig. 7.** Photochemical ozone creation potential (POCP), per functional unit (FU, 1 MJ supplied electricity) of three attributional life cycle assessment scenarios (aLCAp physical allocation, aLC Ae economic allocation, aLC Ac core allocation) and two consequential (cLCA) life cycle assessment scenarios (cLCAl local, cLC Ag general) of an exemplary biogas system in Germany. Average German electricity mix (GEMa) and the marginal German electricity mix (GEMm) are indicated by dotted lines.

#### 4. Discussion

A total of five scenarios were modeled to identify differences in PED and four conventional environmental impact categories. Besides the biogas scenarios, two business-as-usual reference scenarios were analyzed to identify the advantages and disadvantages of electricity generation based on biogas technologies and to be able to give viable input to decision making. The most essential message to communicate is that different methodological approaches, viz. attributional and consequential approach, as well as differences in the assumptions of by-product handling do have a strong impact on the final LCA results. The differences in the reference system were identified to be one major influencing factor on the assessment of the LCA results. Another one was the choice of how to deal with the problem of allocation which affected the total results and the impact analysis of single processes of the biogas system. Physical allocation usually appears to be most scientifically accurate as it uses physical principles instead of societal values. However, mass allocation between milk, meat and manure or biogas and digestate seems to be rather unrealistic with regard to the main purpose of the process. In both cases most of the impacts were not assigned to the main purpose of the process—livestock husbandry or the biogas process. However, if both allocations will be inspected together, application of mass allocation has helped to clearly separate environmental burdens between biogas and animal husbandry systems. In both allocations between milk, meat and manure and biogas and digestate were strongly overlapped by the final allocation between electricity and heat at the CHP. The main idea of economic allocation is that the value is reflected in the price and is thereby a driver of the process (through demand), which means that the price is a valid measure of the proportional value that the society attaches to each. However, an allocation based on prices would lead to an inclusion of an additional economic parameter into the model which has thus far considered only physical quantities. Since market prices, especially those of natural resources might vary strongly – depending on their scarcity – an allocation based on prices can be rather arbitrary. The result of the whole LCA would not be stable over time and thus not comparable to other LCA's. Not only time is an important aspect of variation, prices can also differ strongly between different countries leading to differences in the respective LCA results. For energy allocation between electricity and heat, exergy factors as used in the core product aLCA scenario can be a golden mean as exergy factors reflect both, physical properties as well as the valence of the product compared to energy allocation which reflect

only the physical properties and economic factors which reflect only the market values of the product.

System expansion is the alternative to handle by-product allocation and to foresee true environmental effects of changes induced by products. From a modeling point of view the main advantage of the cLCA approach is the possibility of presenting the total biogas system with all environmental burdens. While the results of an aLCA approach are focused on the impacts going along with the functional unit and is therefore less expressive and transparent. A higher transparency in the cLCA approach on the other hand requires the collection of more specific data. Especially the identification of the marginal technology needs a lot of information about the entire farm and energy systems. Focusing on a specific situation has helped to isolate and reduce the impact of the national and global agricultural and energy market system and thereby the extent of the data collection. In aLCA, data for allocation procedure play a major role for the final results. To guarantee a wide validity of the study data has to be collected if not available in data bases to estimate the impacts going along with the biogas electricity system and the correlated heat and fertilizer systems. In cLCA the definition of the marginal technology system boundary is always going along with the discussion on completeness and topicality of the observed system. Especially against the background that the actual consequences of a change in a farming or energy system are highly variable and will change rapidly during the next years due to expected changes in the European and German agricultural and energy markets. However, the question on where to set the geographical and technical system boundaries to consider all relevant information of the market is one of the main problems. Will the markets be more regional due to higher energy prices or more global due to market concentration? Therefore, a cLCA approach can never describe all consequences of a change as the future energy market situation is inherently variable. This variability limits all attempts to describe future consequences of a change in demand. Another issue going along with marginal products is the functional equivalence of the marginal technology. While this question can be answered quite accurate for energy systems due to technical necessities and requirements, it is more difficult in the agricultural sector. Currently there are different functional references discussed in the agricultural sector, e.g. protein, fat, energy content for food products, nutrient or carbon content for organic fertilizer products. However, the question on which product will be avoided in reality, e.g. milk (no equivalent marginal product), beef (chicken, pork, goat meat, etc.) or manure (mineral fertilizer, organic fertilizer

like compost or nitrogen fixation by legumes), is so far not solved finally.

## 5. Conclusions

The comparison of different LCA approaches applied to the same exemplary biogas system in this study revealed that the calculated environmental performance is affected considerably by the methodology chosen. Allocation to main and by-products had the highest impact on differing results between aLCA and cLCA approach as well as on differences between scenarios within the same LCA approach. The main outcomes of this investigation was that the cLCA approach obtained significantly lower results in PED, GWP, EP and AP while the aLCA obtained lower results in the POCP only when results were set in relation to the reference system. Although total results are varying in the both approaches, the same conclusions regarding the tendency of energy demand and emissions compared to the business as usual situation can be drawn. However, some exceptions were found in contribution, order and type of the hot spots. Hence for more precise analysis, it is of eminent importance to exactly define the goal and scope of the study to make sure that the right methodological approach is chosen and the system boundary is selected adequately.

An aLCA approach should be preferred if the main purpose of the study is to understand the contribution of single hot spots to the environmental performance in order to realize technology specific optimization potentials and in second place to compare biogas plant concepts with different technology status, feedstock supply, etc. In both fields of application the focus lays on the internal benefit for the observed unit (e.g. farm). However, also in aLCA approach interactions with other systems can be tested by a variation of economic allocation factors. However, the price represents only a limited part of an unspecified static economic market.

A cLCA approach should be used if a landmark decision of higher organizations like trusts or governments is needed and global environmental superiority should be proved. Therefore a micro-economic activity (investment in a biogas plant) is connected with macro-economic consequences (substitution of existing plant capacity). Those consequences have to be identified by inspecting a broader range of market interdependence, e.g. technology progress and volume of use as well as market behavior. In both, aLCA and cLCA sensitivity and scenario analysis or dynamic models should be used to test stability of parameters or future changes in frame conditions.

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